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14. ABSTRACT
Development of a compliant Ge-on-Insulator (GeOI) substrate for growth of lattice-mismatched films, i.e. InSb and HgCdTe, was targeted. Fabrication combined the demonstrated compliancy of an ultrathin (< 3 nm) Ge film (on insulator) with nano-engineering of the step structure on vicinal Ge surfaces to yield a substrate with unsurpassed ability to elastically accommodate mismatch strain. Furthermore, since the GeOI growth substrate is Si-based, it is compatible with the wide range of tools for processing Si wafers, and therefore does not poses any inherent size,

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Report Title

Si Based Large Area Substrates for HgCdTe Infrared Detectors: Final Report

ABSTRACT

Development of a compliant Ge-on-Insulator (GeOI) substrate for growth of lattice-mismatched films, i.e. InSb and HgCdTe, was targeted. Fabrication combined the demonstrated compliancy of an ultrathin (< 3 nm) Ge film (on insulator) with nano-engineering of the step structure on vicinal Ge surfaces to yield a substrate with unsurpassed ability to elastically accommodate mismatch strain. Furthermore, since the GeOI growth substrate is Si-based, it is compatible with the wide range of tools for processing Si wafers, and therefore does not poses any inherent size, shape or handling restrictions that would limit its use in manufacturing or scalability to larger-sized wafers. Results to date provide clear evidence of the compliancy of the thin-film GeOI (100) substrate. However, evaluation of growth on a vicinal plane to suppress the formation of anti-phase domains (APDs), has not been completed. APDs are formed as a result of growth of a polar film on a non-polar substrate. Growth has been demonstrated on a 6?-off (100) GeOI substrate, but development of a 4?-off (211) GeOI substrate, as required for growing HgCdTe, has been delayed due to technical issues. These issues have been overcome and efforts continue to demonstrate growth of a HgCdTe/CdZnTe heterosturcture.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

M. C. Debnath, T. D. Mishima, M. B. Santos, K. Hossain, and O. W. Holland, Growth of InSb epilayers and quantum wells on Ge(001) substrates by molecular beam epitaxy,, J. Vac. Sci. Technol. B, Volume 27, Issue 6, pp. 2453-2456.

Number of Papers published in peer-reviewed journals: 1.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

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Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

M. C. Debnath, T. D. Mishima, M. B. Santos, K. Hossain, and O. W. Holland, InSb-based epilayers and quantum wells on Ge-On-Insulator and off-axis Ge substrates Proc. of the 26th North American Molecular Beam Epitaxy (NAMBE) Conference, IX.1, August 9-12, 2009, Princeton University, NJ, USA.

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Patents Submitted

Patents Awarded

Graduate Students

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

<u>NAME</u>

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

The project targeted development of a compliant Si-based substrate for growth of lattice-mismatched films including II-VI infrared-active material. The Ge-on-insulator (GeOI) substrate combines a number of technologies including the demonstrated compliancy of an ultrathin (< 3 nm) Ge film (on insulator) with nano-engineering of the step structure on vicinal Ge surfaces. This technique is designed to yield a growth substrate with unsurpassed ability to elastically accommodate mismatch strain between the substrate and as-grown films. Materials targeted for evaluation include both InSb and HgCdTe, which have a large lattice mismatch with Ge. These materials are used in the fabrication of a wide variety of devices including infrared detectors and focal plane arrays (FPAs), as well as high-mobility field-effect transistors (FETs). Furthermore, since the GeOI growth substrate is Si-based, it is compatible with the wide range of tools for processing Si wafers, and therefore does not poses any inherent size, shape or handling restrictions that would limit its use in manufacturing or scalability to larger-sized wafers.

(As indicated in previously, fabrication of GeOI involves Ge^+-ion implantation of Si-on-insulator (SOI) followed by thermal oxidation. The thickness and composition of the synthesized GeOI depend on the implantation fluence, oxidation ambient, time and temperature. Oxidation is used to segregate the implanted Ge so that it accumulates into a single layer below the thermal oxide. Subsequent etching of thermal oxide with dilute HF acid results a GeOI structure.)

Growth of a polar semiconductor film such as HgCdTe on a non-polar substrate, i.e. Si or Ge, gives rise to defects such as anti-phase domains (APDs), which provide both carrier scattering and recombination sites. Such defects along with misfit and threading dislocations greatly affect the quality of polar films on a Si-based substrate. In attempts to improve the quality of films grown on the GeOI substrate ARI has achieved significant success in synthesizing 6°-off (100) and 4°-off (211) GeOI substrates. The oxidation kinetics of off-axis (100) and (211) Si were evaluated to determine oxidation conditions for fabricating GeOI. Off-axis (100) GeOI was successfully fabricated with a ~3 nm of germanium surface layer. Pre-growth annealing of the off-axis GeOI substrate was used to create an optimal surface morphology, which is required to minimize APD formation in films grown on the surface. While characterization of this surface state is difficult, it has been done using atomic force microscopy (AFM). However, initial studies indicate that micro-Raman is also being able to distinguish between off- and on- axis GeOI substrates. As shown in Fig. 1, a discernable Raman shift was observed between the signals from on- and off-axis bulk Ge substrates indicating a strong dependence on crystallographic orientation. Multiple measurements confirmed these results and demonstrate the validity of this nondestructive characterization tool.

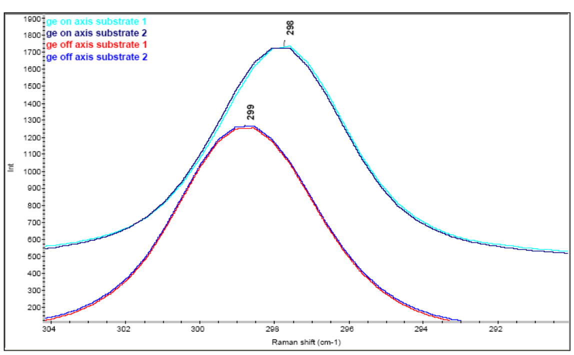


Figure1. Raman shift with crystallographic orientation differences.

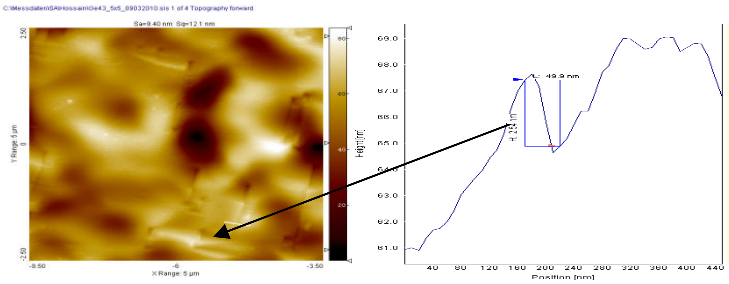


Figure 2. AFM topogrphay indicating steps in off-axis substrates after annealing and before growth

The results in Fig. 2 are of AFM evaluation of the step structure on an off-axis surface after 610°C annealing to attain the double steps required for APD suppression. Although long range terracing and 2.5nm steps made it difficult to identify the double atomic steps required to suppress APDs. However, characterization of InSb films grown on- and off-axis Ge substrate was done using *reflection high-energy electron diffraction (RHEED*). RHEED results in Fig. 3 show a '3×' and 1× pattern in off-axis films along [110] and [1-10], respectively, indicating a single-domain within the film, while the observation of a '3×' patterns along both [110] and [1-10] in the on-axis film clearly indicates the presence of APDs.

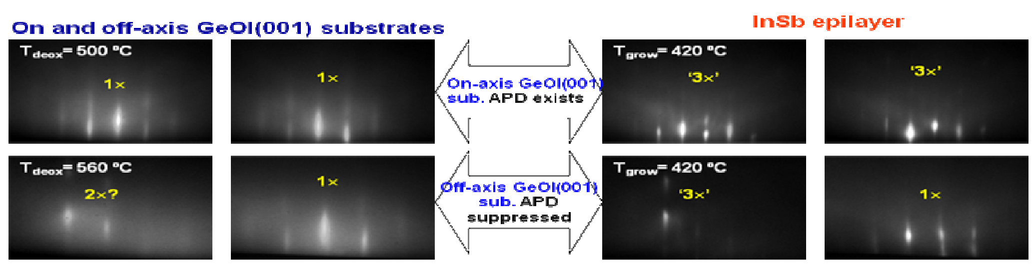
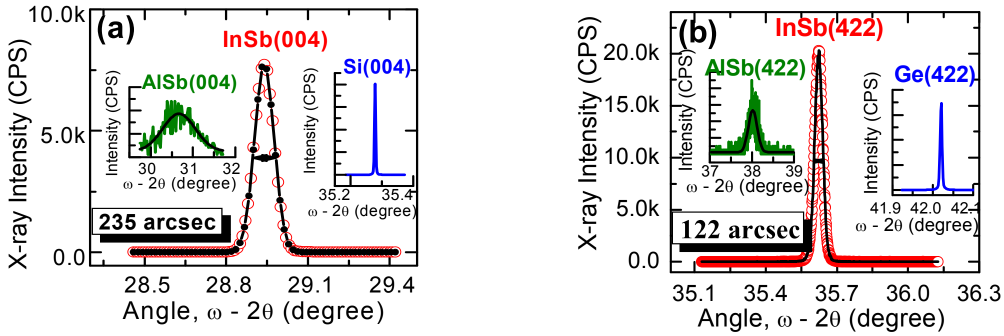


Figure 3. RHEED patterns are compared before and after epilayer growth on and off-axis GeOI (100) along [110] and [1-10] directions. Samples grown on these off-axis substrates suppressed the APDs.

Previously determined, optimized conditions were used to grow InSb epilayers (2.0-μm – 4.0-μm) and Si δ-doped InSb/$Al_{0.210}In_{0.80}Sb$ single quantum wells (SQWs) on both on-axis and off-axis Ge(001), GeOI(001) and Ge(211) substrates. The crystalline quality of the epilayers was characterized using high resolution X-ray diffraction (XRD). Typical XRD rocking curves with ω-2θ scans are shown in Fig. 4(a) and 4(b) for the (004) and (422) Bragg reflection from an InSb epilayer (4.0-μm-thick) using 6º-off-axis GeOI(001) and 4º-off-axis Ge(211) substrates, respectively. The rocking curve width in the InSb epilayer grown on 6º-off-axis GeOI(001) substrate is 235 arcsec as shown in Fig. 4(a). The width is reduced to 122 arcsec for growth on a 4º-off-axis Ge(211) substrate indicated in Fig. 4(b). Figure 4(c) shows the rocking curve width of InSb epilayers as a function of epilayer thickness for the all samples grown on this study and compared with the sample grown on 2º-off-axis GaAs(001) substrate (circles). Among all the epilayers, *the narrowest rocking curve width was obtained for the InSb epilayer grown on the 4º-off-axis Ge(211) substrate which indicates it has the best crystalline quality of the samples.*



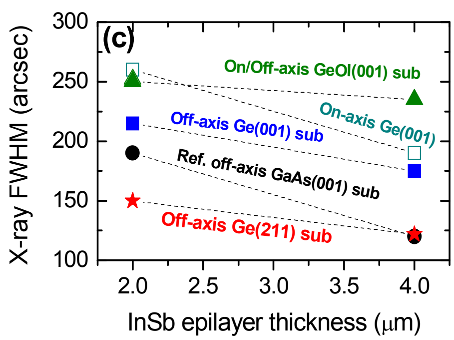


Figure 4. XRD rocking curves of a 4.0-μm InSb epilayer on (a) 6°-off-axis GeOI(001), and (b) 4°-off-axis Ge(211) substrate. (c) X-ray rocking curve width as a function of thickness in InSb epilayers grown under different conditions as follows; squares: on/off-axis Ge(001) substrate, triangles: on/off-axis GeOI(001) substrate, stars: off-axis Ge(211) substrate, and circles: 2°-off-axis GaAs(001) substrate.

The carrier mobility and density of the epilayers and SQWs were investigated by Hall-effect measurements. Figure 5(a) shows the room-temperature (RT) electron mobilities of InSb epilayers (2.0- and 4.0- μm-thick) grown on on-axis Ge(001) substrate (circles), 6°-off-axis Ge(001) substrate (triangles), 6°-off-axis GeOI(001) substrate (squares), 4°-off-axis Ge(211) substrate (stars) and 2°-off-axis GaAs(001) substrate (diamond) for comparison. Among all the epilayers, *the highest RT electron mobility of 61,000 cm^2/V-s was obtained for a 4.0-μm-thick InSb epilayer grown on a 4°-off-axis Ge(211) substrate. This is the highest reported electron mobility for any InSb-based structures deposited on a Ge substrate*. This value is comparable to ~65,000 cm^2/V-s which we typically obtain from a 4.0-μm-thick InSb epilayer grown on a 2°-off-axis GaAs(001) substrate. We found that electron mobilities in the InSb epilayers grown on off-axis Ge(001) substrates and on off-axis Ge(211) substrates are ~1.5 times higher than the InSb epilayers grown on on-axis Ge(001) and GeOI(001) substrates. *The significant increases in RT electron mobilities can be attributed to the suppression of APDs in InSb epilayers by the use of off-axis Ge(001) and Ge(211) substrates, and off-axis GeOI(001) substrate*. Part of the mobility enhancement may derive from the reduction in micro-twin density, which cannot take form in epilayers grown on a off-axis (211) substrate.

The success in improving electron mobility in InSb epilayers by the use of off-axis (001) and (211) Ge substrates motivated us to grow InSb/$Al_{0.20}In_{0.80}Sb$ SQWs on such substrates, as identified in Fig. 4(b). As expected, the RT electron mobilities (12,500 cm^2/V-s) in InSb SQWs grown on off-axis Ge(001) substrate (triangles) and on off-axis Ge(211) substrate (stars) are ~1.5 times higher than InSb SQWs grown on on-axis Ge(001) substrate (circles) and on-axis GeOI(001) substrate (squares) (8,500 cm^2/V-s). Although InSb SQWs grown on both off-axis Ge(001) and Ge(211) substrates have almost the same electron mobilities at RT, *InSb SQWs on off-axis Ge(211) substrate* *exhibit ~2.0 times higher electron mobility (~50,000 $cm^2/V\text{-}s$) than the InSb SQWs on off-axis Ge(001) substrate at low temperatures.*

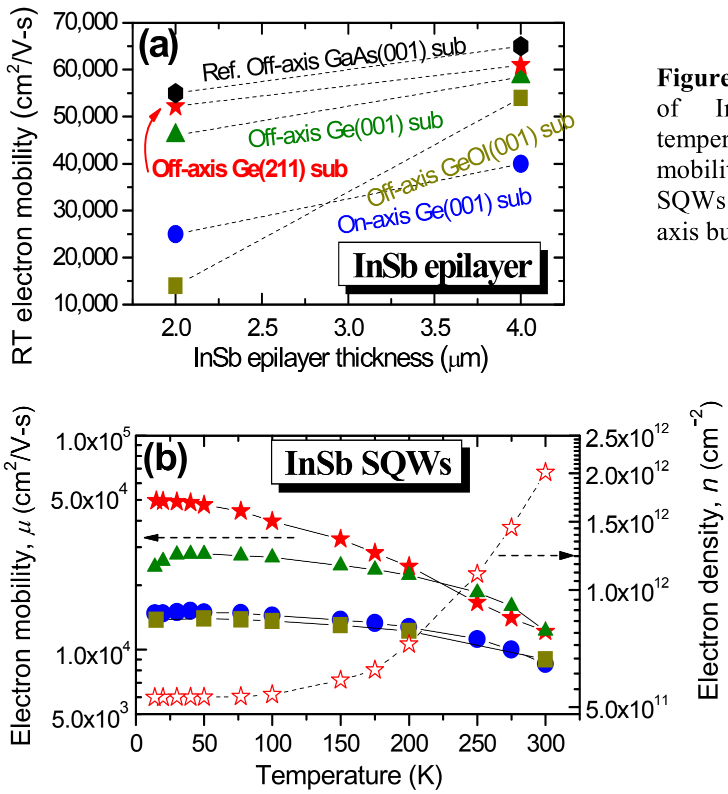


Figure 5. (a) RT electron mobilities of InSb epilayers, and (b) temperature dependence of electron mobilities in $InSb/Al_{0.20}In_{0.80}Sb$ SQWs grown on on-axis on and off axis bulk and thin film substrates

Amethyst Research Inc. (ARI) was unable to complete its evaluation of MBE growth of HgCdTe/CdZnTe heterostructures on (112)-oriented GeOI substrates. Additional time is needed to complete the tasks described in the Statement of Work. This is due to a delay in processing the commercially-acquired (112)-oriented SOI material for use in fabricating the GeOI growth substrate. While this material was oriented appropriately for this study, the superficial or device layer of Si was too thick to be easily thinned as required for GeOI synthesis. In particular, the thinning process involves thermal oxidation of this superficial layer to remove all but a small layer (<10 nm). However, the thickness superficial layer of the (112)-oriented SOI material required almost 100 hours of oxidation to thin it to its targeted thickness. Since ARI had been depending on a contracted third party for the oxidation step, such long oxidation times became both impractical and expensive. To circumvent this problem, ARI decided to acquire the requisite equipment so that it could process the material internally. To this end, ARI has purchased both an oxidation furnace and a fume hood and is presently installing them within its processing facilities. The program delay was unavoidable but growth will resume soon and an initial evaluation of the targeted HgCdTe/CdZnTe heterostructures forthcoming. When these results are available they will be provided to the ARO program manager.